IN2P3 Prospective: X-Ray Astroparticle

A. Goldwurm, A. Coleiro, S. Gabici, C. Lachaud, P. Laurent, A. Lemière, D. Prêle, R. Terrier, P. Varnière (APC),V. Beckmann (CNRS / IN2P3), D. Dornic (CPPM), N. Leroy (LAL), F. Calore (LAPTh, INP), F. Piron (LUPM)

Summary

X-ray astronomy (XRA), intended here to cover also the ranges of hard X-rays and soft gamma-rays, is a crucial window to explore the **cosmic high-energy phenomena of the violent and energetic universe**. This science domain is at the core of the **astroparticle field,** one of the main Institute research branches.

Indeed the study of **accretion and ejection in compact objects, in particular in stellar mass and supermassive black holes, of particle acceleration in relativistic and non-relativistic shocks, of particle interaction in neutral or ionized material, of the detection and investigation of high-energy rapid transients, which are possibly counterparts of events of the newly emerging multi-messenger astronomy, gravitational wave or neutrino signals**, relies heavily on observation and theoretical interpretation of the emitted X-ray radiation.

Other important energetic phenomena in high energy astrophysics, like behaviour of **ultra-dense nuclear matter in neutron stars, hot plasmas and non-thermal emission in galaxy clusters,** which can also play the role of cosmological probes**, dark matter signatures, supernova explosions and emission by their nucleosynthesis products**, and **several others processes**, are also studied mainly using X-ray data. They are all strongly connected to topics (e.g. CMB, Lorentz invariant testing, neutrino physics, etc.) of Cosmology, Theoretical physics and Particle physics.

Even though not an historical research axis of IN2P3, X-ray astronomy appears more and more crucial to obtain scientific advances in particular in discovery and interpretation of electromagnetic counterparts of the sources of the now emerging multi-messenger astroparticle physics that will definitely develops in the coming years. Solid **research programs in core topics of X-ray astrophysics and direct involvement in projects for X-ray observatories**, which are all **space borne**, are therefore **key programmatic elements** to allow the institute to play a leading role in astroparticle science in the next decades.

A **well-defined involvement in X-ray astronomy** by the institute will allow the full exploitation of the fruitful **synergies of XRA with the future large astroparticle experiments** like CTA (TeV gamma-rays), KM3NeT (high-energy neutrino), advanced-LIGO/Virgo (aLIGO/Virgo) and LISA (Gravitational Waves). An effort to better integrate this astrophysics domain in the vision of the Institute for the next 10 years is therefore proposed here, with the aim of confirming and reinforcing the engagement of its laboratories in the missions in operation (XMM, INTEGRAL), in the missions under development, SVOM and Athena, and possibly promoting participation in proposals for future missions like THESEUS and PHEMTO.

A. Energetic processes through X-rays

Soft and classical X-rays (0.1-15 keV), hard X-rays (15-300 keV) and soft gamma-rays (300 keV–1 MeV) are produced in large quantities only in very peculiar high-energy sources most of the time powered by the the huge gravitational wells that compact objects (CO) create in their vicinity or alternatively by the effect of huge magnetic fields also generally related to CO physics.

While high temperature plasmas are present even in relatively close and quiet objects (normal stars, Sun, etc.), undoubtedly the most powerful X-ray emitters are Active Galactic Nuclei (AGN), Gamma-Ray Bursts

(GRB), X-ray compact objects, in binaries (XRB) or isolated (pulsars, magnetars, etc.), and supernovae (SN) and their diffuse or compact remnants, i.e. supernova remnants (SNR), pulsars (PSR) and pulsar wind nebulae (PWN). These objects are all somehow linked to the presence, generation or merging of compact objects, in particular of black holes (BH) and neutron stars (NS).

In addition to their obvious interest as objects predicted by general relativity and the perspective that their observation may shed light on fundamental physics questions related to the interface between classical and quantum theories, we now know that CO and particularly black holes of all masses have a fundamental role in shaping the galaxies and the observable properties of the Universe. The mechanisms of the feeding and feedback between supermassive BH (SMBH) and their host galactic bulges are however still largely unknown and are subject of vast research programs involving large X-ray surveys. They are also objectives of the core science of the next generation of the X-ray observatories developed or prospected by the world main space agencies (ESA, JAXA, NASA).

Certainly accretion and ejection processes around BH (and in general in CO) that generate massive and powerful (sometimes relativistic) outflows are the key to understand such phenomena. Accretion disks emission peaks at ultraviolet and soft X-rays, hot coronae comptonization plus non-thermal accelerations push the X-ray emission in the classical and hard X-ray domains where also the synchrotron emission (possibly highly polarized) of jetted AGN (blazars) or XRBs peaks. Reflection in the disk and absorption and reverberation in close or more distant matter give rise to specific X-ray timing (lags) and spectral signatures (e.g. shifted, enlarged and distorted metal fluorescence lines) that allow to study matter conditions, dynamics and space-time metrics through measurements of Doppler shifts, relativistic smearing and time delays. Gamma-ray prompt emission of GRBs peaking in the MeV range is produced in relativistic jets pointed towards us by hyper-star core collapses or NS-NS mergers while their X-ray afterglows produced by interaction of the jets with the surrounding interstellar material allow to search for counterparts and identifications of these objects and to study their environmental conditions. GRB are observed at very high redshifts and are therefore today also used as cosmological probes and to study the early stages of the Universe.

Observations in the high-energy electromagnetic domain starting at keV energies are therefore fundamental for understanding how matter is organized and behaves around black holes, unravelling how these extreme objects influence their environments on a very large scale, finding the still elusive obscured massive objects in the centers of the galaxies and studying the mechanisms through which gravitational power is converted in particle acceleration and radiation.

Other major problems in contemporary astrophysics, such as the understanding of particle acceleration processes at shocks of all sizes (those of PWN, SNR, but also at larger scales those of AGN radio lobes and clusters of galaxies) in relation to the still mysterious origin of cosmic-rays, also require observations at X and soft gamma-ray energies and are of particular interest for IN2P3 scientists.

The list of astroparticle application cases of XRA is so large that we will not attempt to describe them. We will rather illustrate here, after a summary of present and future XRA missions, a few relevant examples for which either the institute labs have obtained remarkable results showing relevant synergies with other astroparticle facilities, or where the prospect for implications are highest, and discuss these topics following the two main observation strategies: large, deep surveys and time domain observations.

B. X-Ray Missions

The two large observatories that work in the classical band (0.1-12 keV), Chandra (NASA) and XMM-Newton (ESA), are operating since 1999, with typical field of view (FoV) of half degree and angular resolutions of 1”-15”, and will probably be extended up to the mid-20s. INTEGRAL (ESA), operating since

2002, covers the range 20 keV-10 MeV with its main instruments (very large FoV of ~30° and angular resolutions of 15'-2°) and may also be extended till about 2025. Another mission covering the hard X-ray band (3-80 keV) is the Nu-STAR mission which features much better angular resolution (1') and sensitivity than INTEGRAL but much smaller FoV (7'). The Neil Gehrels Swift Observatory, operating since 2004, carries a hard X-ray (15-150 keV) instrument with a large FoV and resolution comparable to INTEGRAL and an X-ray telescope with angular resolution similar to XMM. Its capability to rapidly point transient events after on-board detection with the large FoV instrument has allowed impressive advances in GRB and time domain science. The recently launched (2019) SRG/eRosita Russian-German mission carries powerful X-ray telescopes working in the classical X-ray band and telescopes that detect hard X-rays up to about 20-30 keV. It is dedicated to large surveys particularly focussed at extragalactic astronomy. Few other more specific missions are presently operating: MAXI, AstroSat, HXMT and Nicer. IN2P3 scientists are involved directly in the INTEGRAL mission (APC) and use particularly XMM, Chandra, Swift and NuSTAR as guest observers.

The panorama of planned future XRA missions includes the Chinese-French SVOM mission to be launched in 2021 and the ESA large class mission Athena foreseen for 2031. SVOM is dedicated to the variable transient sky and features a coded mask instrument (ECLAIRs) working in the range 4–150 keV with a 90° x 90° FoV and resolution of 1.5°, coupled to a narrow field X-ray telescope (0.1-10 keV) with 1° FoV and 4' angular resolution, along with a visible telescope and 3 gamma-ray non imaging detectors. SVOM, like Swift, will automatically repoint the GRB as soon as ECLAIRs detect them. IN2P3 is directly involved in the project with 4 laboratories (APC, CPPM, LUPM, LAL) in charge of some hardware components and the preparation of part of the science ground segment and of the scientific programme. Athena is the next large X-ray observatory of ESA operating in the classical (0.1-15 keV) band. Equipped with the new generation of large X-ray mirrors will carry an imaging camera with large sensitivity (WFI) and an X-ray Integral Field Unit imaging spectrometer with spectral resolution of 2.5 eV, FOV of 7' and angular resolution of 5". The extraordinary spectral power (> 1000) of the X-IFU, whose development is under responsibility of France and CNES, will revolutionize the field. The APC laboratory is involved in the development of part of the X-IFU readout electronic chain and in the science ground segment.

Other relevant approved XRA missions are: XRISM (JAXA, NASA), successor of Hitomi to be launched in 2022 that will use X-ray bolometers for an imaging spectrometer expected to reach 7 eV spectral resolution and IXPE (NASA) that will carry early 2020s an imaging polarimeter working in the low energy band. Proposed missions are FORCE (JAXA) for hard X-ray imaging with resolutions better than NuSTAR, THESEUS (ESA, in competition for the M5 selection) for the GRB and transient sky science and PHEMTO (*Polarimetric High Energy Modular Telescope Observatory*) a hard X-ray (1-600 keV) imaging polarimeter mission proposed for the ESA voyage 2050 roadmap (Laurent et al. 2011).

C. X-ray deep observations and large surveys of astroparticle phenomena

X-ray astronomy is nowadays based on observations performed with large powerful observatories like Chandra, XMM-Newton, INTEGRAL that have typical lifetime of 15-20 years. Their performances and life timescales allow scientists to run research survey programs and deep observations able to push the frontier of knowledge even for the weakest objects, unveiling subtle processes previously completely unknown. These capabilities have particular application in astroparticle where the goal is often to search and disentangle weak signatures against the brighter and more standard thermal X-ray emission.

A typical X-ray astroparticle example is the case of the Galactic Center (GC) (Crocker et al. 2015). This region is a unique laboratory for high-energy astrophysics as it is the site of several powerful processes and violent phenomena. In the few central square degrees (~600 x 200 pc² at 8 kpc distance) a variety of peculiar objects interact with each other and with the very dense stellar and interstellar content. The study of the high-energy emission from this so called Central Molecular Zone (CMZ), carried from keV X-rays to TeV gamma-rays, is crucial for the understanding of the interplay between these objects, computing the region overall energy budget and studying the energetic feedback between the GC and the Galaxy, processes that are likely at work also in other galactic nuclei (Ponti et al. 2015).

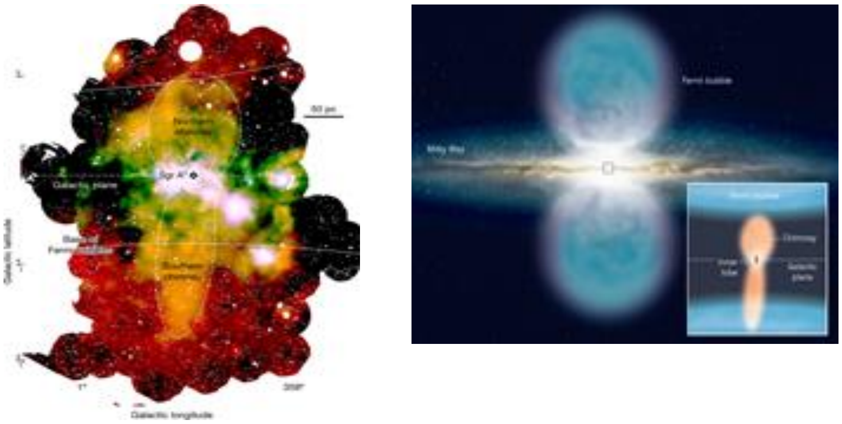

Figure 1 XMM soft X-ray image around the GC showing the hot plasma chimneys that extend north and south of Sgr A* connecting the region to the base of the Fermi Bubbles (Ponti et al. 2019). Artistic view of the Fermi Bubbles and schematic picture of the X-ray chimneys connecting them with the GC (Chernyakova 2019).

The most important of these objects is the compact radio, infrared (IR) and X-ray source Sgr A*, firmly associated to the 4 million solar masses SMBH of the Galaxy. Sgr A* is very dim at all frequencies. Long and deep searches in X / hard X-rays have revealed that the source has luminosity as low as 10^{-11} its Eddington luminosity at these energies, which has prompted the development of accretion theories (advection dominated models) and MHD simulations of low accretion rate BH that are now applied to low luminosity BH in XRB and GN. These surveys have also led to the discovery of random flares in X and IR at a rate of 1/day and durations < 2 hr, during which Sgr A* luminosity can increase by up to factor 200. These flares offer nowadays a unique possibility to study processes that occur at few gravitational radii from a SMBH horizon in optically thin conditions and are targets of multi-wavelength campaigns from radio to TeV gamma-rays (Ponti et al. 2017).

They however cannot explain the increasing number of indications that the GC has been very active in the past. The most compelling of these are certainly the gamma-ray Fermi bubbles, huge lobes of GeV gamma-ray emission detected by the Fermi satellite extending symmetrically towards both galactic poles from the GC regions. They must be created by large GC activity either in form of star formation episodes or AGN-like phase of the SMBH. Another crucial observation of high energy activity from the GC is the TeV emission coming from a central source (compatible with Sgr A*) and from the molecular clouds (MC) of the CMZ observed by the Hess experiment. Detailed studies of Hess data accumulated over > 10 years indicate the presence of a PeVatron of cosmic rays illuminating the CMZ and producing the diffuse TeV emission (Hess coll. 2016, Jouvin et al. 2017). These results need to be confirmed and explained and the GC will certainly be a priority target for CTA.

The CMZ/GC X-ray surveys appear now the best way to study the putative past activity of the GC. Using INTEGRAL, XMM, CHANDRA and NuSTAR scientists, including IN2P3 researchers, have shown that Sgr A* likely underwent few giant outbursts that rose its X-ray luminosity by a factor of 1 million in the past few hundred years. Traces of these events are found in the X-ray emission of the molecular clouds of the CMZ, that reflect with some delay the X-ray emission of a source that is today off and is most likely the SMBH. The reflected emission by cold material displays specific non-thermal features, fluorescence line of neutral iron at 6.4 keV and hard X-ray continuum above 10 KeV, that are used to determine the Sgr A* light curve in the past millennium (Terrier et al. 2018, Chuard et al. 2018).

But the large XMM X-ray surveys of the CMZ and GC polar regions have also allowed to find traces of more powerful and more ancient activity. IN2P3 researchers and collaborators have found that large chimneys of hot plasma extend from the central regions to the base of the gamma-ray Fermi Bubbles establishing for the first time a clear connection between these features and the GC (Ponti et al. 2019, Fig.1).

Given its large gravitational potential well the center of the galaxy is also suspected to concentrate Dark Matter. A spherical GC GeV excess extending approximately over the galactic bulge (FWHM~10°) has been detected with Fermi and interpreted as signal from annihilation of cold dark matter particles. Investigations whether it can be due to an astrophysical signal (the main working hypothesis is that of an additional population of millisecond pulsars is responsible for it) rely on multi-wavelength surveys able to disentangle these populations (Bartels et al. 2018), with X-rays playing a major role, in particular considering that the GeV signal appears spatially correlated to the 511 keV electron-positron bulge emission measured with the INTEGRAL and which is itself one of the big mysteries of galactic astronomy (Prantzos et al. 2011).

Breakthrough advances on all these topics will be provided by the future X-ray missions, and in particular by the next generation of X-ray spectrometers based on bolometers (XRISM, Athena). Their exceptional spectral resolution will allow the detailed study of the fluorescence lines emitted by the MC and the thermal lines of the hot plasma that traces the giant outflows in the region or the Sgr A* inner accretion flow, providing exceptional diagnostic power of the dynamics, physical conditions and ultimately the origin of these phenomena. X-ray polarimetry (IXPE, PHEMTO) will also further constrain some of these processes, in particular those originated by synchrotron mechanisms (Sgr A* flares) and also those due to reflection, allowing in particular to further constrain MC location and therefore age and characteristics of past Sgr A* outbursts. All these future X-ray surveys will have clear synergies with CTA and also with LISA which will look for merging processes with the galactic SMBH.

In a more general way, identifying TeV sources that will be detected by Cherenkov gamma-ray telescopes involve large multi-wavelength observing campaigns and in particular a search for X-ray counterparts which allows to unveil their nature and disentangle the physical processes at work (e.g. leptonic vs hadronic).

For instance, XRB can be followed over long timescales to distinguish the physical changes that take place in the systems (accretion disk, corona and relativistic jets). In the past decades, the availability of multiple X-ray missions (including INTEGRAL) dramatically changed our vision of these sources. Combining archival data and new observations allowed to obtain new insights into the accretion/ejection coupling but also made the full picture more complicated. Different accretion and ejection properties lead to different spectral, timing and polarization signatures at high energies which make INTEGRAL well suited to explore these processes thanks to its wide FoV, its Galactic-plane monitoring, an energy coverage up to several MeV and its good polarization capabilities. In particular, INTEGRAL brought unique contributions in the study of the spectral high-energy cutoff continuum from Comptonization of accretion disk photons and the excess emission (hard tail) observed in several sources (e.g. Rodriguez et al. 2015). While the exact origin of these features is still debated, INTEGRAL observations provide a direct insight into the black-hole corona and/or the relativistic jet. While these sources are mostly outside the field-of-view of the SVOM satellite, systematics (spectral and temporal) surveys of XRB outbursts will be performed with the

SVOM/ECLAIRs instrument to better understand the physics, driving their evolution, their impact on the surrounding interstellar medium and eventually the Galaxy.

Moreover INTEGRAL instruments have very good polarimetry capabilities up to several hundreds of keV. Although polarimetry measurements are challenging and require long exposures, the first detection of hard X-ray (above 400 keV) polarization in the XRB Cyg X-1 (Laurent et al. 2011) is a breakthrough result which might be an indication that the hard tail spectral component comes from the relativistic jet. The detection of hard X-ray polarization remains challenging for other XRB since most of them are transient and faint sources. While the detection of the X-ray polarization of V404 Cyg was claimed by Laurent et al. (2016), one will have to wait for future space missions dedicated to polarimetry measurements such as the PHEMTO that will operate from 1 keV to ~600 keV with performances several orders of magnitude better than the present hard X-ray instruments.

Given the mission constraints optimized for GRB search, the general program of SVOM mission will be exploited to survey the extragalactic sky in particular for AGN of all kinds that are the most luminous persistent objects of the Universe (Beckmann & Shrader 2012). Likewise for galactic XRB, SVOM will allow to survey the 4-150 keV energy range dominated by the accretion disk reflection and the hot corona emission of these BH accreting systems thanks to the large FoV ECLAIRs instrument. Whin a typical year of operation ECLAIRs is expected to detect 250 AGN, mainly Seyfert type galaxies, and for the 30 brightest persistent of them (mainly absorbed Seyferts) it will provide detailed spectra giving the continuum slope and the Compton reflection fraction. The brightest and variable objects will be then pointed with the narrow field instruments that will provide simultaneous multi-wavelength data.

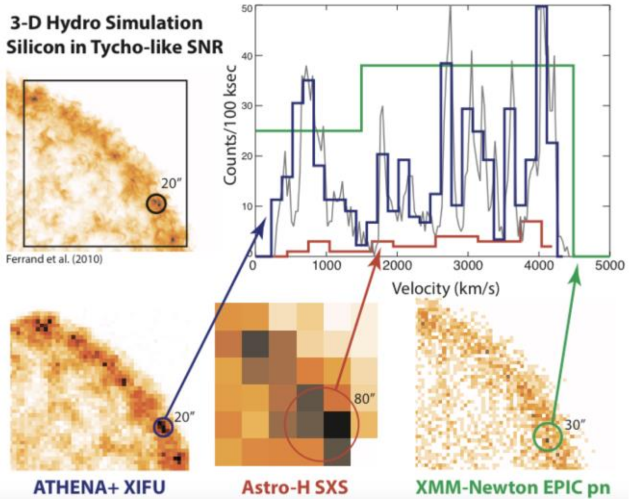

Figure 2. ATHENA/X-IFU, ASTRO-H and XMM-Newton images and silicon velocity profiles from a 3D hydrodynamic simulation of Tycho’s supernova remnant. It shows the capability of Athena to retrieve the 3D dynamics of the SNR to quantify its ability to accelerate cosmic rays. From Decourchelle et al., 2013.

Most of the cosmic rays observed at Earth are of Galactic origin, in particular up to the so-called knee of the cosmic-ray spectrum, occurring around 3×10^{15} eV. While supernova remnants (SNRs) are usually considered as a good supplier of cosmic rays in the Milky Way, there is still no conclusive evidence that they are indeed the primary source of Galactic cosmic rays nor that SNRs can accelerate protons up to the knee. Measuring the energy content of SNR cosmic rays requires a combination of gamma-ray and X-ray datasets. Indeed, X-ray data are necessary to model the thermal emission that provides the density and composition of the SNR which are then used to model hadronic interactions and convert gamma-ray luminosity into cosmic-ray energy output. However, if the X-ray emission is dominated by synchrotron processes, the thermal component cannot be detected and thus it turns out impossible to constrain the hadronic contribution to the gamma-ray emission since the plasma density is not constrained anymore. X-IFU high-spectral resolution measurement will allow for the detection of emission lines (see Fig. 2) above strong non-thermal continuum. Their thermal Doppler broadening will be used to measure ion temperature which is related to cosmic-ray acceleration efficiency.

D. Time domain X-ray astronomy

In a few decades, astronomy moved from a static point of view on persistent sources to a dynamical approach consisting in observing variable and transient sources, over a broad range of frequencies and timescales. This emerging domain allowed not only for a great improvement in our understanding of the accretion/ejection processes at all scales (gamma-ray bursts, microquasars, AGNs) but also for new discoveries such as fast radio bursts and tidal disruption events. This was made possible thanks to significant technological developments of wide field-of-view detectors, at all wavelengths, and in particular in the X-ray domain.

In addition to the multi-wavelength approach, multi-messenger astronomy is now entering a new era not only with the first detections of gravitational-wave (GW) signals emitted by stellar-mass compact objects, but also with the observation of high-energy astrophysical neutrinos. While both of them open new perspectives for understanding high-energy phenomena close to stellar-mass as well as supermassive black holes, the detection of an electromagnetic counterpart is still crucial to develop a full picture of these phenomena.

A particular example is the hard X-ray INTEGRAL/SPI-ACS and Fermi/GBM detection of the binary neutron star merger GW170817 (Abbott et al. 2017, Savchenko et al. 2017) discovered by gravitational wave interferometers (aLIGO/Virgo), which has shown that multi-messenger astronomy and particularly X-ray and soft gamma-rays bring crucial new insights into these violent phenomena, first helping to localize the source and then, through longer-term follow-up, to unveil the dynamics and the geometry of the (relativistic) ejecta. From 2021, SVOM will be one of the key projects devoted to the study of the transient sky. It will operate in close synergy with aLIGO/Virgo interferometers as well as the KM3NeT neutrino telescopes in order to address the main questions of multi-messenger astronomy: i) the understanding of the physics and progenitors of gamma-ray bursts, ii) the understanding of stellar-mass compact object mergers and iii) the origin of high-energy cosmic rays and neutrinos.

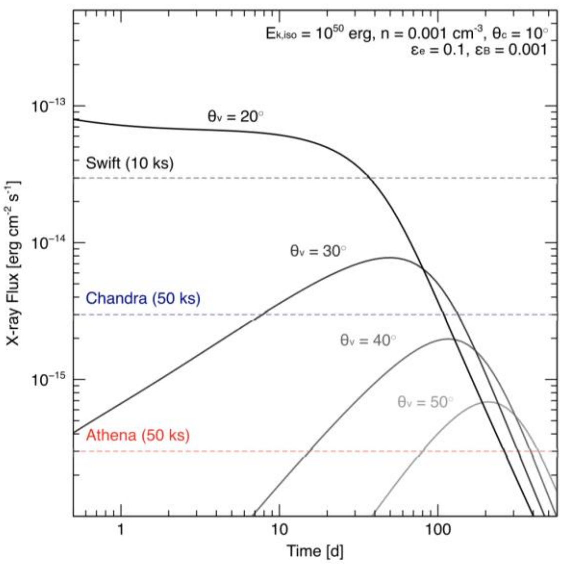

Figure 3. Predicted X-ray light curves of GW counterparts for different viewing angles, assuming a standard afterglow at 100 Mpc. Swift, Chandra and ATHENA sensitivities are reported. From Troja et al, 2018.

In the same context, THESEUS, proposed in response to the ESA call for medium-size mission M5, was selected in 2018 to enter an assessment phase study until 2021. If finally selected, THESEUS will fly in 2034 with the aim of surveying (high-redshift) transient sources through its payload composed of a wide FoV (~1sr) X-ray (0.3-6 keV) monitor, an infrared telescope with both imaging and spectroscopy capabilities and a set of coded-mask cameras sensitive to hard X-rays and soft gamma-rays over the broad energy range [2 keV - 20 MeV]. Operating simultaneously, THESEUS will provide real-time triggers and accurate position of high-energy transients for Athena that will ensure a deep follow-up through ToO observations starting within 4 hours from the trigger with both WFI and X-IFU to unveil the nature of GRBs and of stellar-mass compact object mergers. In particular, thanks to its high sensitivity, Athena should be able to detect off-axis GRB afterglows for a significantly broader range of viewing angles (see Fig. 3) and distances. At all redshifts, X-IFU will be able to probe the environment of GRB host galaxies, in order to trace the metal enrichment of the Universe as well as to map the earliest formation sites of (population III) stars. This is crucial to further understand cosmic reionization, formation of the first seed black holes and the evolution of metallicity across the Universe.

The understanding of the evolution of stellar-mass black holes as well as the physical processes leading to GRBs will certainly move forward in the next few years thanks to the increasing sensitivity of GW interferometers (aLIGO/Virgo and the 3rd generation ground-based Einstein telescope) and the development of electromagnetic follow-up networks both at ground and into space. On the contrary, the question of how do supermassive black holes (SMBHs) at the center of galaxies form, grow and accrete matter will probably remain largely open during the next decade. However, in early 2030s, Athena and LISA will trace the growth of supermassive black holes and accretion processes taking place in their vicinity. LISA is designed to observe the low-frequency (0.1 mHz – 1 Hz) GW signal emitted by merging SMBH binary systems, and the combination of its data with those of Athena will likely revolutionize our understanding of SMBH physics. In particular, the possible detection with Athena of an X-ray counterpart to a (pre-)merging SMBH or a low-mass compact object orbiting a SMBH detected by LISA will open the door not only to a better understanding of the accretion processes powering AGNs, their close environment and the jet launching, but also to independently constrain the Hubble constant and the speed of gravity. In that way, LISA and Athena data will turn out to be highly complementary, the former bringing information on the binary system configuration while the second will provide key insights into the physical and radiative processes at play.

The question of physical processes leading to relativistic jets in AGNs can also be addressed from another perspective. In particular, unveiling their composition (hadronic vs leptonic) will allow for a better understanding of their formation and acceleration, and is closely related to the mystery of the origin of high-energy cosmic rays, at the hearth of IN2P3 research topics. As of now, TeV-PeV astrophysical neutrino observation offers one of the best ways to tackle this issue, provided that electromagnetic follow-ups are performed quasi-simultaneously. The possible association between the IceCube neutrino event IC170922A and the gamma-ray blazar TXS 0506+056 led to an intense electromagnetic follow-up campaign which allowed for a full coverage of its spectral energy distribution, from radio to high-energy gamma-rays. While single-zone hadronic models could not succeed in explaining both the electromagnetic and neutrino detections, lepto-hadronic models provide physically-consistent picture with gamma-rays produced by inverse-Compton processes and high-energy neutrinos produced by a radiatively sub-dominant hadronic component, tightly constrained by X-ray observations. Indeed, secondary particles produced by photo-hadronic processes should emit X-ray (keV-MeV) synchrotron radiation and thus, regular X-ray monitoring of blazars (and other possible high-energy neutrino sources) looks essential to constrain hadronic acceleration in relativistic jets. In this context, Athena, THESEUS and the proposed mission PHEMTO will play a central role in proving the origin of high-energy cosmic rays by following-up neutrino candidates detected by KM3NeT and IceCube.

PHEMTO will also provide with accurate hard X-ray polarization measurements that will be crucial to further study magnetic field topology and more generally non-thermal acceleration processes. For example, both leptonic and hadronic models for blazar jet emission predict X-ray/gamma-ray polarization signatures (e.g., Zhang & Böttcher 2013) but the level of polarization above 10 keV is substantially higher for hadronic processes. Combined with multi-wavelength polarization observations, PHEMTO will thus distinguish leptonic from hadronic scenarios in AGN relativistic jets. Such studies are in line with the detection of GRB modulated polarization with INTEGRAL, that enabled to constrain the prompt emission processes (Götz et al. 2014), and in which IN2P3 laboratories were involved. Accretion/ejection processes are ubiquitous and happen at all scales, in AGNs, GRBs as well as X-ray binary systems, with timescales and typical sizes potentially proportional to the black-hole mass. While detecting hard X-ray polarization is complex and requires high fluxes, Polarization of the X-ray binary Cyg X-1 was also detected with INTEGRAL, opening new perspectives in our understanding of relativistic jets at different scales.

E. Conclusions

At the same level as cosmic rays, high-energy neutrinos, gravitational waves, and high and very high-energy gamma rays, X-rays from keV to MeV energies are key vectors to explore the violent and energetic universe and the connection between the two infinites. Large number of the XRA scientific topics are within the core science of the astroparticle field, a now well consolidated research branch of the IN2P3 institute, with important repercussions in cosmology, theoretical and particle physics. XRA present and future observatories have and will have more and more synergies with the classical astroparticle experiments and the institute shall not miss the opportunity to collect the full science return of its investments, especially considering the new emergent field of multi-messenger and transient sky astrophysics. In addition to vast guest observer programs, direct involvement in development and operation of XRA missions shall therefore be supported. This implies a solid involvement in space science and technologies with a consequent effort (already well in progress) that will however provide a high-valued return not only on scientific grounds but also on programmatic and public visibility, with the need to develop specific expertise, acquire rigorous management habits and establish fruitful and prestigious connections with the main world space agencies (CNES, ESA, JAXA, NASA) and the major national (CEA, INSU) and international space research institutions. Athena and SVOM missions are particular strategic opportunities. Athena will have extended synergies with LISA, as both missions will explore, from X-rays and GWs respectively, the same SMBH population that shape our Universe while SVOM mission will explore in X-rays at the same time than aLIGO/Virgo and KM3NeT the stellar size BH and NS mergers. These two projects concentrate a large effort of French space programmatics in the next decade. The institute has a potential to exploit these synergies in full and shall catch the opportunity to convincingly participate in these programs.

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